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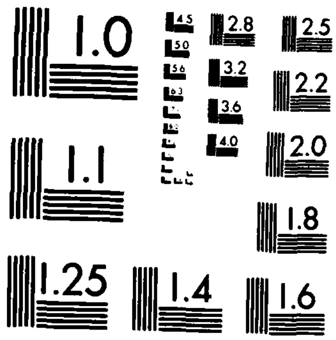

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This contract includes work on two distinct projects.

Task A. Construction of zonal models for computation of complex turbulent flows.

Task B. Study of turbulence structure and heat convection in turbulent boundary layers on concave surfaces.

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For period ending

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15 March 1985

I. General Introduction

This is the annual report for contract AFOSR #F49620-84-K-0004, covering "Theoretical and Empirical Studies of the Basic Structure of Turbulent Shear Flows, Including Separated Flows and Effects of Wall Curvature." The period covered is Jan. 1 through Dec. 31, 1984.

This contract includes work on two distinct projects.

Task A. Construction of zonal models for computation of complex turbulent flows.

Task B. Study of turbulence structure and heat convection in turbulent boundary layers on concave surfaces.

Tasks A and B are discussed in separate sections in the report that follows.

II. TASK A: BACKGROUND

1. Introduction

In section II, we review the status of work on turbulence modeling starting from the results of the 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows. We also include results from a number of current projects with the HTTM group in addition those supported directly by ASOSR Contract F49620-K-84-0004. We use this somewhat unusual reporting method for two reasons. First, it is only in this larger context (over both time and projects) that the implications of the work under this contract can be fully understood. Second, we believe overall picture of the work may be useful information for AFOSR.

In section III of this report we provide the usual sort of details on the specific work on zonal modeling under this contract for the 1984 work period.

2. The Status of Turbulence Modeling -- 1985

2.1 The Status in 1981

The 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent flows provided a thorough picture of the state-of-the-art in computation of turbulent flows in at that time. This picture revealed two central problems:

(a) No method was available that allowed assessment of numerical errors independent from possible errors arising from the particular turbulence model used;

(b) The programs that were fast enough for day-to-day engineering problem solving (mostly $k-\varepsilon$ methods) were not sufficiently accurate. While they performed well in some cases, they did badly on others--sometimes exhibiting an error an order of magnitude in size, and/or wrong trends. Moreover, there were no general rules indicated whether good or bad performance was to be expected in a given instance.

The Conference also stimulated two suggestions for somewhat different approaches than had been taken in the past.

(c) At the Conference Professor J. H. Ferziger and Dr. R. G. Rogallo pointed to the use of Full Simulation of the complete (unaveraged) Navier-Stokes Equations (FTS) and also to Large Eddy Simulation (LES) as tools that could supply results EQUIVALENT TO LABORATORY DATA. The first FTS results, by R. Rogallo of NASA Ames laboratory were presented to the conference as an illustration of the types of results that could be obtained.

(d) S. J. Kline in an OPINION published in Vol. II of the proceedings suggested that the second difficulty arose from the attempt to model many types of turbulence, each complicated in nature, with a model of insufficient generality, that is power. He suggested use of "zonal models" which adjusted one or a few simple and relatively fast models to a well defined taxonomy of flows, case by case; and indicated that such models might be more successful in the long run for engineering problem solving than attempts to seek universality by overgeneralization of mathematical models of limited power.

(e) The Conference also suggested that the need for good data had not yet passed. It was noted that there are still many cases where models were not yet adequate, and also where good data did not exist. It was further noted that virtually without exception history had shown that good data as input for modeling had been required before we achieved adequate modeling in specific cases.

2.2 Strategy in HTTM Following 1981

Since 1981 the work on turbulence within the Thermosciences Division at Stanford has carried forward work along all five of the lines suggested above. This was a conscious decision since it appeared that not only were all lines of work needed, but that syncretism would probably arise from the convergence of several these lines of work. In particular, it seemed to the HTTM group at Stanford that the combination of FTS and LES on the one hand with simpler models (for example, $k-\epsilon$ or equivalent) on the other held important promise for several reasons.

First, given existing supercomputers, FTS and LES methods are capable of providing results that are not measurable in the laboratory. One can set up "pure situations" such as "pure strain", or "pure shear" without the constraints that walls and other requirements impose on real flows. One can also compute the pressure-strain correlations, the complete dissipation, etc., that cannot be measured by known laboratory techniques. One can vary strain rates, and other parameters systematically without the constraints of typical wind-tunnels. In sum, one can obtain output that is directly useful for the formation and checking of simple models more effectively than is possible in typical experiments. There are of course, severe current limits on FTS and LES. The work is very expensive, and the Reynolds numbers and the number of mesh points that can be achieved with existing supercomputers are both distinctly limited. However, one expects that these conditions will be alleviated with further progress in supercomputer size and speed so that there is good reason for pushing forward the methodology as well as seeking explicit current results.

Second, the HTTM group had achieved very good results with zonal models for limited classes of flows of considerable complexity--particularly diffuser flows. Both historical and current (1981) results in other research groups indicated similar results for a considerable number of other cases. The Evaluation Committee of the 1981 Conference remarked that such methods were as accurate as the more complex and slower methods for the cases presented.

Third, the HTTM group was a clear leader, and had been largely responsible, in cooperation with NASA Ames Research center, for pioneering LES and FTS, and thus was in a good position to develop and exploit further results of this type.

Fourth, active studies adding to experimental data on concave walls, for blowing on convex walls, for cases with high intensity turbulence in the outer flow, and for reattachment and recirculating regions were being done within HTTM. These experiments lend much insight to the needed modeling. There remains an important need to reflect these insights more fully in the modeling, and hence there is importance in executing both the experimental and modeling work within a single group.

Fifth, the U.S. Office of Naval Research funded several years ago a joint program between Computer Science and Thermosciences with the objective of improving numerical methods in CFD. This work obviously has potential syncretism in the problem of providing appropriate estimates accuracy of numerical algorithms and in providing robust, fast-running numerical schemes.

2.3 Recent Advances and Outlook in Early 1985

From the viewpoint of early 1985, it appears the syncretism suggested above is being realised. We are gaining important new insights into turbulence physics and turbulence modeling. It seems likely that we will be able to model many turbulent flows of significant technical interest reliably over the next few years. Since we are, in part, describing potential rather than present reality, we are not yet sure how far the successes we are beginning to achieve will allow us to go in terms of the complications of flows that can be treated. However, a few more years work at the present rate of progress should go a long way toward settling this question.

We have been finding that using the results of FTS and LES studies to study fast-running models is particularly valuable. The results do show that one needs to adjust the simpler models case by case if accurate results are to be achieved. The form achievable from FTS and LES results is such that simple manipulation in computer software in the form of "as if" studies can be done very rapidly in microcomputers. This facilitates and speeds model formation significantly.

Recently, Lee and Reynolds of HTTM have shown that all of the data for homoeneous turbulent flows can be fit with a Reynolds stress type of model only if the model is extremely complicated. Their current model contains something like partial differential equations.

On the other hand, in a study of the same homogeneous flows, S. Tzuoo, a current PhD student supported by this grant, has been able to obtain excellent results for all cases with simple models. The standard k-ε model* gives adequate results in some cases, but poor results in equally many cases. Tzuoo's zonal models provide results of adequate accuracy in all cases with comparable running times.

In a separate study C.T. Wu, another current PhD student, has found important information about "compressed turbulence". These are cases of very low Mach number where the flow is compressed by actions in the flow field, for example, in a piston-cylinder flow with the valves closed. Wu showed that the k-ε required significant modification to predict these flows.

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*Standard model here denotes the most widely used constants set into the form of the Launder-Rodi-Reece model used by roughly half of the entrants into the 1981 Conference. The model is held constant for comparative purposes.

These current studies of Tzuoo and Wu suggest an avenue for further development of models. Both results show that one cannot use the standard k-ε model in 'zones' where the rate of strain is high, and the turbulence production is significantly larger than the turbulence dissipation. When Ferziger and Wu looked to see why this was so, they found that the 'ε' equation is used in the standard k-ε model to represent both a length scale of the turbulence and the rate of turbulence dissipation. The model works reasonably well when the production and dissipation are in rough balance, but must and does fail when they are not.

Wu's work also indicates that the time-scale-of-straining compared to the time-scale-of-relaxation of turbulence is an important parameter. When the strain rate is high compared to the relaxation rate, rapid distortion theory provides a useful predictor and limit.

Tzuoo's work was carried out along different lines but pushes toward the same central conclusion. In Tzuoo's homogeneous cases, he found that he needed, in effect, a third equation to create models that give accurate results, and this was particularly true at high rates of strain. Also there was a uniform tendency for k-ε models to become worse as strain rate increased.

Both Wu and Tzuoo obtain results over the full range of strain rates, it appears that they have formulated adequate, fast-running models for the cases covered. Extensions of these results to four other types of flows are in progress: (i) free-shear layers (jets, wakes, mixing layers) [by Tzuoo]; (ii) boundary layers [by Bordalo]; (iii) separated flows (backstep) [by Avva]; (iv) swirling flows [by Zakhem]. Details of these projects are given in Section II below.

In view of reservations expressed by research workers in the turbulence community about zonal models on the basis of the potential difficulties of blending one zone into another, it may be useful to note that in Tzuoo's work the simplest form of blending, a first order lag model, has been entirely sufficient.

It is also important to note that the difficulties in the ε, or dissipation, equation were to be expected. The Evaluation Committee of the 1980-81 Conference noted that this equation appeared to be a weak spot in the models employed in the Conference. In a similar vein, the results in the 1980-81 Conference also indicated that the models were fairing badly, almost without exception, in regions where the flow was readjusting from one type (say a free shear layer) to another (say an attached boundary layer). These regions are also regions where production and dissipation will not be in equilibrium, and hence this result reinforces the findings of Tzuoo and Wu regarding where the standard model fails, why it fails, and what needs to be done to create improved models.

In another current PhD study in HTTM, S. Caruso, has found a simple, elegant solution to the problem of providing output of guaranteed numerical accuracy. This method grew from the collaboration with Computer Science, in particular from the dissertation of Berger done under the direction of J. Oliger. In this method one uses Richardson extrapolation. The essence of the method is as follows. After a converged solution is reached, one repeats the computation WITH A DOUBLED GRID SIZE. By subtracting the solution with the doubled grid size from the normal converged solution at the original mesh size, one can form in a very simple way an ESTIMATE OF THE NUMERICAL ERROR AT EVERY POINT IN THE FIELD. This information has several important uses.

First, one can reduce the grid size until the error is reduced to less than a specified input parameter. Second, one can use the information to develop an ADAPTIVE GRID solution method that is far more efficient than simple reduction in grid spacing over the entire field. Caruso has constructed such a method. Thus far, he has applied it to a jet flow slanted at 30 degrees to the grid direction and to the backward-facing step. The details of this program will not be given here, but it is important to note that the method is fully automated and gives reduction in computing times from 7 to 30 fold. This gain becomes rapidly larger as increased accuracy is demanded. Further gains in speed are expected.

A third and unanticipated benefit also arises from this adaptive grid method. The method shows, as a normal output, the regions of flow sensitivity. For example, in the backward step, the contour plots of numerical errors show high values concentrated in the region just downstream of the step corner. This is in accord with our knowledge of the physics of this flow. That is, small changes in the corner region have a much larger affect than small changes at any other point in the field; we know this is correct from detailed laboratory studies on this flow. Thus the careful plotting of numerical error indicates important aspects of the physics; it shows us the regions of sensitivity that are critical for control and for good designs. One suspects this result will be general, but we have only one case thus far. and hence do not want to overestimate at this time.

The work on the adaptive grid method, as a method for providing adequate estimates of numerical accuracy is sufficiently advanced that we are recommending to Prof. G. M. Lilley that the error estimation procedure be made a mandatory part of the next "trials" of computer output with data, that is the follow-on to the 1980-81 meeting. We are also urging all workers in CFD to seriously consider adopting this method or an equivalent.

This adaptive grid method, when coupled with our zonal models, gives promise of providing very efficient methods for computing turbulent flows of practical interest. This coupling remains to be studied. Also the results of the zonal cases have only been completed for homogeneous flows, for compressed turbulence and are largely complete for planar jets. Thus we are not yet far enough along to claim success over a large domain for the zonal approach. Nevertheless enough has been achieved so that we are optmistic about the outcomes over the next few years.

III. Task A -- Goals and Progress

1. Goals

The goal of Task A is to investigate the use of zonal models for rapid, accurate computation of complex turbulent flows, including provision of adequate estimates of numerical accuracy.

The approach to be used was provided in a separate document to AFOSR on methodology for zonal modeling in late 1983. Additional copies can be supplied if needed.

Recent historical background and context for the work are given in section II above.

2. Status of Work

2.1 Completed Work

A set of zonal models for homogeneous turbulence subject to pure shear or pure strain has been developed. A readjusting parameter governed by a first-order differential equation is used to patch the zonal models. Excellent agreement with full-simulation results and experimental data by use of such zonal models have been achieved. This work successfully confirms the feasibility of the zonal idea for complex turbulent flow modelings and provides a starting point for such tasks. A complete report has been written.

2.2 CURRENT WORK

2.3a. Modeling of Free Shear Flows

Work has essentially been completed for the two-dimensional jet. In this flow, the standard $k-\varepsilon$ model works adequately, provided sufficient care is taken to give accurate initial conditions. Since it is a shear flow with only modest and decaying turbulence production rates, it is consistent with the results reported in section III.2.1 on when $k-\varepsilon$ methods will succeed.

In the work on the two-dimensional jet, a method was devised for studying the details of the flow as a function of transverse location. It was found that the structure parameter and the type of simple modeling that works well varies, depending on whether the point studied is between the centerline and the inflection beyond or beyond the inflection point. this kind of detailed study provides information that will aid in formulation of accurate models.

The second phase of the work involves the zonal approach for free shear flow modeling. First, a detailed flow structure for turbulent jets from experiments has been studied. An experimental data base was built for both co-flowing jets and jets into still air. A computer code was written to solve such flows. The standard $k-\varepsilon$ model was first tested. The centerline velocity and spreading rate by standard $k-\varepsilon$ model give good agreement with data.

During 1985, the same kind of study as for the two-dimensional jet will be done for round jets, radial jets, mixing layers, and, if time permits, two-dimensional ans axisymmetric wakes.

2.3b Attached Turbulent Boundary Layers

The goal of this portion of the study is to provide models for attached turbulent boundary layers covering effects of pressure gradient, blowing/suction, and temperature-dependent properties.

A numerical algorithm has been written that solves the boundary-layer equations using a nonuniform, adaptive, staggered grid. The Keller box method of differencing was tested and found to be inadequate. The Crank-Nicholson method, however, appears to work satisfactorily. Current efforts are focusing on testing turbulence models in this numerical scheme.

2.3c. Separated Flows

A numerical code was written to solve the 2D Navier Stokes equations for laminar flow regimes. The code employs a more accurate modification of the SIMPLER method developed by Patankar which solves the momentum equations and a poisson equation for pressure iteratively in a sequential manner. Conversion to 3D is relatively straightforward and turbulent flows can be computed by adding turbulent transport equations.

It is a fairly common practice to use central differences to approximate the diffusion terms and upwind differences to approximate the convection terms in the momentum equations even though the upwind differencing renders the scheme only first order accurate. On the other hand, central differencing of convection terms causes instability and consequently wiggles in the solution, if the the cell Reynold's number is greater than 2. However in a majority of the computational situations, the cell Reynold's number is considerably greater than 2 and so central differencing is almost never used.

Besides being only first order accurate, the upwind differencing introduces artificial or numerical viscosity which may give rise to unrealistic solutions. As most turbulent flow solvers employ Boussinesq's eddy viscosity concept, addition of any artificial viscosity naturally imparts inaccuracy. This makes it very difficult to test turbulence models as the numerical and model errors can not be separated. The normal cure is to refine the grid to decrease the numerical viscosity. Adaptive gridding provides an alternative.

APPENDIX: CENTRAL DIFFERENCE METHOD

We have developed an efficient and yet simple method to eliminate the drawbacks associated with the upwind differencing.

Consider a system of finite difference equations

$$Lu\ U(n+1) = S \tag{1}$$

where

Lu is a difference operator using upwind differencing for the convection terms.

U(n+1) is the field variable at (n+1)st iteration.

S is source term.

This system converges but the converged solution is inaccurate.

To remove this inaccuracy, we add a correction term to the source as shown below:

$$Lu\ U(n+1) = S + Lu\ U(n) - Lc\ U(n) \tag{2}$$

where

U(n) is the field variable at nth level of iteration,

Lc is the differenced operator constructed using central differencing to approximate the convection terms.

At convergence

$$U(n+1) = U(n)$$

So system (2) at convergence reduces to

$$Lc\ U = S$$

Note that the converged solution U is 2nd order accurate due to Lc and the system (2) converges without any instabilities due to the stability properties of Lu.

The method (2) has been tested on a 2D square cavity problem at an Re of 400 and the results have been found to be very encouraging.

Work for the 1985 period will apply this procedure to the backward-facing step. This case has several advantages for the present purposes: (i) it is the standard test case; (ii) it has available data with varying parameters (channel angle) from the 1981 new cases; (iii) it has the variety of zones necessary to make a strong test of zonal modeling.

2.3d. Swirling Flows

This phase of work was begun late in 1984. Work to the end of 1984 consisted of a literature survey. Work during 1985 will be concentrated on selecting appropriate cases for simulation. And formation of tests to determine why existing models fail, and to begin construction of means to overcome the difficulties.

TASK B

THE TURBULENCE STRUCTURE AND CONVECTIVE HEAT TRANSFER IN A TURBULENT BOUNDARY LAYER ON A CONCAVE SURFACE

1. Goals

1.1. Introduction

Kreith* first showed, in 1955, that concave curvature increased heat transfer, although the fact that curvature affected the turbulence structure had been known since the early 30's. Between 1955 and 1967, there does not appear to have been much activity. In 1967 Schneider and Wade measured heat transfer in a curved-duct flow, and in 1968 Thomann made local measurements of boundary-layer heat transfer in a supersonic flow with convex and concave curvature. In every instance, concave curvature resulted in an increase in heat transfer. The increase was assumed by many to be the direct consequence of streamwise vortices within the boundary layer, caused by a Taylor Görtler instability, but there was dissent. Eskinase and Yeh (1956) reported an increase in heat transfer, but no evidence of streamwise vortices. The issue has become increasingly important as aircraft engine designers have pressed closer and closer to the limits of assurable prediction of heat transfer. It is desirable to be able to predict the heat-transfer coefficient within 5% on a turbine blade, yet this cannot be done at the present state of the art. Most of the current prediction programs for boundary-layer heat transfer are two-dimensional. If Taylor-Görtler vortices are important in the concave-wall boundary layer, then three-dimensional codes will have to be developed. On the other hand, if the increase in heat transfer is a result of a generally increased turbulence activity, but still two-dimensional, then existing codes can be simply modified to acknowledge the curvature effect, and no major changes in computational philosophy need be undertaken.

The objective of this work is to identify the mechanism whereby concave curvature increases the heat transfer through a turbulent boundary layer. This involves careful documentation of the fluid mechanics and of the heat transfer. It is necessary to establish a well-qualified flow on a concave surface, demonstrate that the heat transfer is increased, and then determine the fluid-mechanic and thermal behavior of the boundary layer carefully enough to establish whether or not streamwise vortices played an important role. As in most convective heat-transfer problems, the fluid mechanics must be thoroughly understood before the heat-transfer study can be begun.

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*References listed here are in the report HMT-35, listed at the end of this section.

1.2 Background and Objectives of the Fluid-Mechanics Study

Concave curvature has a relatively large, unpredictable effect on turbulent boundary layers. Past studies of turbulent boundary layers on concave walls have emphasized quantitative, single-point measurements. For example, skin-friction and turbulence levels are shown to increase when the boundary layer goes from a flat wall to a concave wall. However, there is disagreement over the cause of these results. Some recent studies have reported large-scale, spanwise variations in mean velocity and skin friction to support the idea that an array of large-scale, counter-rotating vortices exists within the concave turbulent boundary layer--structures similar to the Taylor-Gortler vortices seen in laminar boundary layers on concave walls. However, in other studies these large-scale variations were not found. Even among those who did find stationary, large-scale variations, there are inconsistencies in the relative size and spacing of the variations compared with the boundary layer thickness and the radius of curvature, the most reasonable length scales. Furthermore, the effects of concave curvature on the basic elements of the boundary-layer structure (e.g., streaks and bursts) have not been studied, and at the start of the original study, no adequate picture of the overall flow field existed.

The general goal of this study is to obtain improved qualitative and quantitative understanding of concave turbulent boundary layer flow. The knowledge gained should permit development of more realistic computational models of the fluid dynamics for use at all levels, from integral equations up to the full Reynolds stress equations.

The findings and accomplishments of the first phase of the fluid dynamics studies are summarized in the final report (May, 1984) on the original contract, AF-0010. Complete technical details are given in the three references by Jeans and Johnston (1982, 1983, and film supplement to Report MD-40).

In summary, a new channel-flow facility for the study of concave turbulent boundary-layer flow was designed and built. Studies of the flow were carried out using flow visualization (dye injection into the wall layers and hydrogen bubbles). In addition, the hot-film velocimetry method was employed to obtain profiles of mean velocity, $U(y)$, and profiles of fluctuation, $u'(y)$, about the mean. The fluid is water at a mean speed of 15 cm/sec. The flow develops over a long (4.9 m) flat surface before it enters a 90° concave bend (wall radius = 134 cm). the opposite wall of the channel is contoured to cause the static pressure along the test surface to be constant. At the start of the bend, the boundary layers are 8 cm thick and fully turbulent ($U\theta/\nu$ = 1300 to 1400). The flow has good spanwise two-dimensionality.

In the studies of Jeans and Johnston, it was shown that the basic instability mechanism that creates laminar Görtler cells also acts in the turbulent boundary layer over a concave surface. However, the expected stable laminar pattern of longitudinal vortices was not seen. Rather, a pattern of large-scale structures, now referred to as roll-cells, appears in the concave region of the test surface. These cells are neither stationary in space or time, and their longitudinal extent is only two to four times their length scales in the y and z directions. The latter scale is of the order of the boundary-layer thickness, much larger than the largest eddy sizes in the turbulence. The quantitative data showed that the development of the roll-cell structure had profound effects on the mean-velocity profiles and the turbulent fluctuations. However, the quality of the U and u' data was not satisfactory for further detailed study of the flow.

The objectives of the current program, under AF-0004, were formulated in 1982, and we started to carry them out in 1983. Much progress (outlined below) was made in 1984. Our objectives are to:

(i) install and modify, as required, the two-component (u and v) LDV system on the concave wall facility. This has been accomplished and excellent data obtained.

(ii) investigate means for stabilizing the spanwise locations of the longitudinal roll cells so that detailed studies of their turbulence structure might be accomplished. this is completed and reported in Barlow and Johnston (1985). Carefully sized and placed vortex generators were used for roll-cell stabilization.

(iii) Study, in all feasible ways, the quantitative features of concave-wall, turbulent flow structure. In particular, we want to find the mechanisms by which the large-scale features, the roll cells, affect the structure of a turbulent layer so that more rational approaches to its modeling, at practical and fundamental levels, may be made.

1.3 Objectives of the Heat-Transfer Study

The primary objective of the heat-transfer study was to determine whether or not streamwise vortices (that is, Taylor-Görtler vortices) played a significant role in raising the heat-transfer rate on a concave wall. The concept of a streamwise vortex involves an organized motion of the fluid over a long streamwise distance--such structures cannot be detected at any single point. Furthermore, there is no assurance that such structures, if present, would be stationary--they might meander. The measurement problem was thus expressed in the following form: devise a way to find out if the increase in heat transfer is due to large-scale structures within the boundary layer, whether they are stationary or meandering.

The requirement for "full-field" knowledge suggested that the best approach would be a visualization technique, applied over the entire surface, which would make visible the heat-transfer coefficient distribution everywhere at the same instant. Such a technique had already been developed, at Stanford, for steady-state use in air. Application to transient studies in water seemed feasible, and this approach was selected for the study.

The overall program then consisted of the following steps:

1. Develop a curved-wall tunnel which produces a flat-plate boundary layer with normal characteristics at the entrance to a concave test section.

2. Qualify the visualization method for accurate mesurement of mean heat transfer on a flat wall in water.

3. Qualify the visualization method for unsteady heat transfer at frequencies as high as might be expected of a meandering vortex.

4. Demonstrate that the average heat transfer on the concave wall is larger than on the flat wall by the expected amount (20-30%), all other factors remaining fixed.

5. Photograph and interpretExamine the wall-visualized distribution of heat-transfer coefficient, looking for evidence of streamwise structures.

2. Accomplishments

To preserve the structure thus far established in this report, the accomplishment of the fluid-mechanic and heat-transfer studies are reported separately. This should not be construed to mean that the two programs were run independently--far from it. Professors Johnston and Moffat worked closely together in the planning, execution, and interpretation of the results, as did the research assistants.

2.1 Fluid Mechanics

Details of the first phases of work are contained in the 1982 publications by Jeans and Johnston. The recent work covering 1983 and early 1984 is in the paper by Barlow and Johnston. We are still working to achieve better interpretation of the data already produced. The on-going work will establish a more complete data base and a physically based model of this complex flow.

Specifically, the accomplishments of the past year are:

(i) We completed the installation and modifications to the laser-velocimeter system so that we are able to measure instantaneous u and v velocity components. At any particular streamwise (x) station, we can control the traversing unit to produce profiles normal to the wall, y-direction, or spanwise to the wall, z-direction, over a distance of $\pm$ 20 cm with respect to the centerline of the flow. Our current data on u appears to be accurate down to y^+ values of 1 to 2, and v is accurately measured from $y+ = 4$ to 5 out to the edge of the boundary layer.

(ii) A semi-automated data-acquisition system is in place. u, v, and probe position are continuously recorded on our laboratory VAX and the records used for detailed analysis. For a single location in the flow, data-acquisition rates are fast enough, and acquisition times long enough (2 to 5 min.) to allow frequency analysis over the full range of interest; over a range of periods from about 200 sec down to 1/50th of a sec. the latter corresponds to a time scale shorter than viscous decay scale of the smallest eddies, and the former is typical of the roll-cell lifetime.

(iii) At the end of the year, we were nearly finished obtaining our first full set of data for cases with and without roll cells. These include complete u, u', v', and <u'v'> profiles at the upstream flat station, and at 15, 30, and 60° of turn in the curved region. When the vortex generators were in place, complete profiles were taken in both inflow and outflow regions, between two adjacent roll cells (see Barlow and Johnston, 1985).

(iv) Near the end of the year, we started to develop software that will, we hope, enable us to use the raw u' and v' data records to detect sweeps and bursts at various y^+ locations. The uv quadrature method of Bogard and Tiedermann appears to be working well for this purpose. The VITA method is also under investigation. Both are being checked against visual observations of the burst frequency in the flat-wall part of the flow. Comparison of flat-wall results on burst-detection frequency to similar data from the concave region was started in early 1985.

(v) A method for extracting spectra from the u', v', and <u'v'> data was developed during the year. Some preliminary studies of these spectra have been carried out for the preparation of an abstract offered to the 5th Symposium on Turbulent Shear Flow, Cornell, Aug. 1985, Barlow and Johnston, "Velocity Spectra for turbulent Boundary Layers on a Concave Surface."

(vi) We have attempted to investigate the inner layers of the boundary layer below $y^+ = 40$ and down to $y^+ = 1$ to 2, in great detail. The primary motivation is the importance of these inner layers in the convective heat-transfer process. In addition, in the earlier work of Jeans and Johnston, we were unable to measure u(y) close to the wall. Consequently, wall shear stress was deduced indirectly from the Clauser plot using standard constants. Because of the curvature effects, this hypothesis needed to be checked. In Barlow and Johnston (1985), we were able to show, by direct measurement of dU/dy in the region of $y+$ from 2 to 5, that the Clauser plot method is satisfactory except in one case. It yielded values of C_f that were 10 to 20% too high under the inflow regions between two roll-cells for the case when the cells are stabilized in spanwise location by the vortex generators. We are continuing to investigate the potential of our measurement system for inner-layer studies. For example, we have been able to replicate the data of Kreplin and Eckelmann, and we hope to be able to extend this work in the future.

2.2 Heat Transfer

The heat-transfer coefficient distribution has been made visible on a concavely curved surface covered by a turbulent boundary layer. The average heat-transfer coefficient was about 20% higher than would have been expected on a flat wall, but there was no evidence of large-scale streamwise structures. The wall image showed a structure of slowly undulating streaks having a lateral spacing of about 200 wall units and a streamwise length of about 1000 units. These values are very close to the values observed for the thermal structures on a flat wall, studied with the same technique. The spanwise variations in heat transfer were about ± 15% both on the flat wall and in the curved region. With one exception, the thermal streaky structure in the curved region was not distinguishably different from the pattern on the flat wall. The one difference noted was the intermittent appearance of large, isolated, "star-burst" patterns on the streak structure of the curved wall. During one of these events, the normally-parallel streaks in the wall image would suddenly diverge, forming a fan of rays pointing in the generally downstream direction. The divergence angles of the outermost rays would typically be on the order of 30-45°, top to bottom. The star-burst pattern would persist for several seconds, and then disappear by dissolving. The image did not convect downstream and did not appear to be washed out from its edges; it simply dissolved.

A 16 mm color motion picture was made of these events, in the flat and in the curved region, and transmitted to the Air Force*. The details of the study are contained in a Thermosciences Division Report, HMT-35, by Simonich and Moffat, which has also been transmitted.

We believe that this study has established conclusively that the increase in the average heat-transfer coefficient in the concave region is not due to the direct action of streamwise vortices "scrubbing" the surface. As a corollary, then, we believe that the concave-wall heat-transfer problem can be handled by two-dimensional boundary-layer codes such as STAN5, given an appropriate model for the enhanced mixing.

To demonstrate the use of a two-dimensional program, a mixing-length model was installed in STAN5 and adjusted so that it successfully predicted the heat transfer.

The next phase of the experimental work on the heat-transfer portion of the program is awaiting the conclusion of the current round of hydrodynamic investigations. This delay in the heat-transfer work was anticipated in the proposal for 1984.

During this year, a new Research Assistant was added to the group, Mr. Keith Hollingsworth. He replaces Mr. Kevin Stoll, who elected to seek employment in industry after completion of his Master of Science degree in December. Mr. Hollingsworth came to Stanford in September as a post-master's student seeking a Ph.D. in the Thermosciences. His research efforts since his arrival have been in familiarizing himself with the concave-wall heat-transfer problem, and learning to operate the experimental apparatus and instrumentation currently being used in the hydrodynamic study. It is expected that the transition from the hydrodynamic study ot the heat-transfer study will be made more quickly and efficiently as a result of this training.

During the first half of 1984, the heat-transfer surfaces were taken out of storage and inspected for damage. The thermocouple probe was redesigned, and the new frame for the probe was built. The probe will be strung during the next academic quarter.

The methodology for making the next set of heat-transfer measurements was described in the last report. The technique involves coordinating video recordings of the color patterns on one panel of the liquid crystal surface in the concave wall to the signals from the multi-point thermocouple sensor spanning the boundary layer on that panel. When a large-scale event occurs, records of the temperature distribution through the boundary layer are stored and keyed to the visual record of the event stored on videotape. two new additions to this methodology are presently being considered. first, the success of the present work with the LDV system used in the hydrodynamic study has led us to consider the use of the laser in both an LDV mode and as a flow-visualization aid in investigating the large-scale heat-transfer events. Second, we are investigating the possibility of digitizing the color images of

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*A copy was provided to AFOSR, Division of Mechanics, Bolling Air Force Base, in March of 1982.

the heat-transfer surfaces. Image digitization would provide a quantitative record of the distribution of the heat-transfer coefficient and allow calculation of the space/time averages during an event. this will greatly expand the utility of the visual records and could find applications in other work involving liquid-crystal surfaces.

With the present hydrodynamic study in its final stages, heat-transfer measurements should begin again in the near future.

3. Reports and Papers from Work under Part II of the Contract

Barlow, R. S., and Johnston, J. P., "Roll-Cell Structure in a Concave Turbulent Boundary Layer," AIAA-85-0297, presented at AIAA 23rd Aerospace Sciences Meeting, Reno, Jan. 14-17, 1985.

Jeans, A. H., and J. P. Johnston, "The Effects of Concave Curvature on Turbulent Boundary-Layer Structure," Structure of Complex Turbulent Shear Flow (R. Dumas and L. Fulachier, eds.), Springer-Verlag, 1983, pp. 89-99.

Jeans, A. H., and J. P. Johnston, "The Effects of Streamwise Concave Curvature on Turbulent Boundary-Layer Structure," Report MD-40, Thermosciences Div., Mech. Engrg. Dept., Stanford Univ., June 1982.

Jeans, A. H., and J. P. Johnston, "Turbulent Boundary Layers on Concave Walls," 16 mm film supplement to Report MD-40. Contact J. P. Johnston, Mech. Engrg. Dept., Stanford Univ., Stanford, CA 94305.

Simonich, J. C., and R. J. Moffat, "A New Technique for Mapping Heat-Transfer Coefficient Contours," Review of Scientific Instruments, 53:5, pp. 678-683, May 1982.

Simonich, J. C., and R. J. Moffat, "Visualization of the Heat Transfer through a Turbulent Boundary Layer on a Concave Wall," HMT-35, Mech. Engrg. Dept., Stanford Univ., Stanford, CA 94305, August 1982.

Simonich, J. C., and R. J. Moffat, "Visualized Heat Transfer from a Turbulent Boundary Layer on a Concave Wall," 16 mm supplement to Report HMT-35.

Simonich, J. C., and R. J. Moffat, "A Liquid-Crystal Technique for Visualization of Convective Heat Transfer," 16 mm supplement to the article in the Review of Scientific Instruments.

IV. TASK C

FINAL COMPLETION OF THE DATA LIBRARY ON MAGNETIC TAPE

Principal Investigators: Profs. B. J. Cantwell and S. J. Kline

Summary

Work has been completed on the data tape resulting from evaluations of the 1980 meeting of the 1980-81 AFOSR-HTTM-Stanford Conference. A geographic breakdown of where the tapes have gone is given on the following page. Table III-1.

Explanation and Detail

One of the major tasks for the 1980-81 AFOSR-HTTM-Stanford Conference was the construction of a machine-readable Data Library of evaluated complex turbulent flows. This library now exists in the form of a magnetic tape (Tape 1) and now contains a total of 60 cases. Tape 1 has been distributed to approximately 71 research groups at universities and corporations around the world. This constitutes the bulk of the research groups active in turbulent CFD.

Because of the large amount of data, five cases were handled "off-tape" in the 1981 meeting. These five cases have now been put into standard form and added to the tape.

Case 0281 - Relaminarizing Flow

Case 0282 - Relaminarizing Flow

Case 0113 (P2) - Asymmetric Flow in a Square Duct.

Case 0422 (P2) - Backward-Facing Step Variable Opposite-Wall Angle.

Case 0423 (P3) - Backward-Facing Step Turned Flow Passage. Data completed and checked. Ready for processing.

March 27. 1984

Table III-1

RECIPIENT BREAKDOWN
Complex Turbulent Flows Data Tapes

Total tapes sent = 71. domestic = 37 international = 34.

Industry = 26
Educational = 31
Military/government = 14

71

UNITED STATES = 37

13 - industry
13 - educational
2 - Air Force
7 - NASA

SWITZERLAND = 1

1 - industry

AUSTRALIA = 2

2 - educational
5 - educational
2 - military/government

UNITED KINGDOM = 8

1 - industry

CANADA = 2

2 - educational
3 - educational

WEST GERMANY = 4

1 - industry

ISRAEL = 1

1 - military/government

YUGOSLAVIA = 1

1 - educational

ITALY = 1 JAPAN = 12

1 - educational
4 - educational

8 - industry

THE NETHERLANDS = 2

2 - industry

END

11-86

DTIC